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Influence of milling on the development of stress corrosion cracks in austenitic stainless steel

K.N. Lyon [a], T.J. Marrow [b], S.B. Lyon [a,*]

[a] Materials Performance Centre, School of Materials, University of Manchester, Oxford Road, Manchester M13 9PL, UK
[b] Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK

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ABSTRACT

We have examined the influence of mechanical surface finishing on the development of residual stresses, and on the subsequent formation of stress corrosion cracks, in 316Ti austenitic stainless steel after exposure to boiling magnesium chloride. The surface residual stresses of as-received plate, prior to machining, were found to be biaxial and compressive. However, abrasive grinding produced significant compressive stresses in the machining direction but much lower perpendicular stresses. On the other hand, milling produced high biaxial tensile stresses (approaching the ultimate tensile strength, UTS, of the material), which were found to be relatively insensitive to cut depth but to vary as a function of feed rate. On the milled surfaces a distinctive pattern of stress corrosion cracking was evident with longer primary cracks nucleating along the milling direction and secondary, shorter, cracks nucleating perpendicularly. As the surface tensile stress was lower perpendicular to the milling direction, we postulate that the nucleation of primary cracks parallel to machining must be driven by the surface profile after machining (and associated micro-stresses) as much as by the macroscopic residual stresses.

1. Introduction

Environmentally assisted cracking is one of the most harmful localised damage processes and encompasses a wide range of mechanisms that includes, for example: hydrogen induced cracking, hydrogen embrittlement, corrosion fatigue and stress corrosion cracking. Typically initiating at local physical features in the material, cracks subsequently develop through various stages of growth from: (i) the formation of multiple short cracks, (ii) the coalescence of these cracks and, eventually, (iii) generation of a dominant long crack that propagates to failure. Cracking generally starts at local defects, which may be microstructural features within the body of the material or, more typically, commence from surface features that are initially present as a consequence of materials processing (e.g. local microstructure, surface roughness) or arise from an in-service damage process such as wear, erosion, or corrosion (e.g. pitting). For austenitic stainless steels, which are the first-choice workhorse alloys for industrial applications requiring corrosion resistance, a key susceptibility is to stress corrosion cracking in environments containing chloride ions where an applied (i.e. service) or residual tensile stress is also present. Chloride-induced stress corrosion cracking of ferrous alloys necessarily commences from a component surface because access to the external environment is required and generally occurs on austenitic microstructures, since ferritic phases are relatively immune from such damage. Thus, the nature of the material surface and near sub-surface (i.e. microstructure, near-surface residual stress and surface geometry) is critical to the initiation and propagation of stress corrosion cracks.

Machining involves considerable localised plastic deformation, generating thermal energy, both of which might give rise to residual stresses. The controlling factors for the generation of surface residual stress during machining were first evaluated by Henriksen (1951). He suggested (for low carbon steel) that residual stresses are primarily generated from plastic deformation rather than differential thermal expansion. For carbon steels, the nature of the residual stress is somewhat dependent upon the hardness of the materials, thus Matsumoto et al. (1986) showed that stresses are tensile for softer steels and tend to become compressive for harder steels. However, in most cases a tensile stress state is left at the surface after machining. According to Brinksmeier (1987) the size of this tensile residual stress, and the depth of the region influenced by the stress, tend to increase with feed rate and cutting speed. For pure turning operations, Leskovar and Peklenik (1981) showed that tensile residual stresses dominate and increase with turning speed; similarly El-Khabeery and Fattouh (1989)

* Corresponding author. Tel.: +44 161 306 4846.
E-mail address: stuart.lyon@manchester.ac.uk (S.B. Lyon).

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showed that for pure milling operations a greater depth of cut and greater feed rates led to larger and deeper tensile residual stresses.

Regarding austenitic steels, Boothroyd (1975) has noted that they are particularly challenging to machine because of their high work-hardening rate and their galling tendency. Jang et al. (1996) and M'Saoubi et al. (1999) found that, after turning of cylindrical specimens, a plane stress condition existed on the machined surface where the hoop stresses were predominantly tensile (and influenced by the cutting conditions), with the axial stresses compressive (and relatively independent of cutting conditions). Kuroda and Marrow (2008 a,b), examined a range of turning conditions in austenitic stainless steel, also finding that the hoop stress was tensile, while the axial stress could be tensile or compressive; tensile stresses tended to develop with high feed rate and low cut depth. The sub-surface hoop and axial stresses were compressive, and insensitive to cutting conditions. In conventional cutting the volume of the thermally affected zone is relatively small compared with the zone of plastic deformation. However, the given the low thermal conductivity of austenitic steels, computer simulations also by Jang et al. indicated that thermal expansion of the surface during machining would occur resulting in greater tensile stresses on cooling compared with ferritic materials. Peyre et al. (2000a,b) have demonstrated changes in the surface microstructure of austenitic alloys after peening with influence on corrosion resistance. This was ascribed to the intrinsic high work-hardening rate of austenite combined with the rapid surface deformation that resulted in a high near-surface dislocation density and it seems likely that this mechanism would also be valid during high speed machining. On the other hand, Miguelez et al. (2009) suggested that residual stresses arise from thin thermally-affected layers which produce thermal expansion and subsequent plastic flow, though such a mechanism may also be dominated by residual stresses generated at the interface at the base of the sheared chip of the plastic region with the surrounding elastic material. Overall, previous work confirms that the surface residual stress distributions in alloys after final surface machining depends on a number of complex and interrelated parameters, including: cutting speed, feed rate, depth of cut and tool geometry as well as the nature of the near-surface microstructure.

Many mechanical failures in service result from an interaction of stresses in the material and the environment. One critical process is stress corrosion cracking (SCC) that, for austenitic stainless steels, almost always initiates from a pre-existing corrosion pit and is largely controlled by the chloride ion concentration, temperature and time in service. Surface preparation plays a significant role in aiding corrosion pit nucleation through the combined or independent effects of: (i) geometry associated with surface roughening, and (ii) the influence of roughness on surface chemistry. For example, it is well known that the localised corrosion susceptibility of stainless steel in chloride solutions is significantly affected by surface finish. Thus, Burstein and Pistorius (1995) and Zuo et al. (2002) both found that metastable pits initiated more easily on rougher surfaces because of the greater number of sites available for such pitting to occur. However, metastable pits have a higher probability of transforming to stable pits on smooth surfaces since more rapid diffusion rates tends to prevent re-passivation. This is because, in many cases, the survival of pit precursors (i.e. metastable pits) has been shown to depend on the maintenance of an effective diffusion barrier formed by salt films (Hong and Nagumo, 1997) or by lacy metal covers over pit mouths (Ernst and Newman, 2002). Additionally, Moayed et al. (2003) qualitatively demonstrated, using both potentiostatic and potentiodynamic critical pitting temperature experiments, that the pitting resistance tends to increase with increasing surface roughness.

Stress corrosion cracking occurs as a chemo-mechanical embrittlement phenomenon in nominally tough and ductile alloys at stress intensity factors (K_{IC}) considerably lower than the nominal fracture toughness of the material. For example Vinoy et al. (1996) found that for AISI316L steel in acidified boiling sodium chloride, the critical threshold for the development of SCC K_{ISCC} was 13 MPa m$^{-1/2}$ (for annealed material) and 10.5 MPa m$^{-1/2}$ (for sensitised material) and for austenitic stainless steels K_{ISCC} is generally between 10 and 20 MPa m$^{-1/2}$. Recently, there has been interest in studying the effect of residual fabrication stresses, primarily cold work, on the susceptibility of stainless steels to SCC, particularly in high temperature water for nuclear applications (Tice et al., 2009) but also in chloride environments (Ghosh et al., 2011) where they found that cold working resulted in significant local formation of deformation-induced martensite in AISI304 and hence increasing susceptibility to SCC. The influence of surface finish (R_a) on SCC of AISI304 under simulated atmospheric corrosion conditions, as a consequence of differing surface finishing operations (predominantly grinding and abrasive wheel milling), was found to result in very high levels of surface tensile residual stress (~1000 MPa, determined by hole drilling) with stress corrosion cracks on ground surfaces found to originate at corrosion pit sites (Turnbull et al., 2011). The influence of surface microstructure on SCC of machined AISI304 stainless steel in a "U"-bend geometry was studied by Ghosh and Kain (2010) where they ascribed a five times increase in the crack density (i.e. number of cracks per unit surface area) in machined samples compared with annealed samples to the surface tensile stresses (which were not measured), surface grain refinement and surface martensite formation. However, many of these studies are unsatisfactory in neither quantifying crack morphology nor surface stresses nor surface roughness.

Overall, therefore, the effect of surface roughness and sub-surface residual stress on the initiation and propagation of stress corrosion cracks remains unclear. The aim of this work, therefore, is to examine how stress corrosion cracking develops as a function of varying machining parameters and, hence, whether there is a systematic relationship in observed cracking between local surface morphology (i.e. machining profile) and residual stresses present in the material.

2. Experimental procedure

2.1. Sample preparation

Rectangular samples (10 × 12 × 19 mm) were cut from a rolled plate of AISI 316Ti (16.9%Cr, 10.8%Ni, 2.0%Mo, 1.6%Mn, 0.59%Ti, 0.08%C, balance Fe). This alloy is a stabilised grade of austenitic stainless steel that is used in moderately elevated temperature applications where the preferential precipitation of titanium carbide rather than chromium carbide provides resistance both to sensitisation (i.e. grain boundary chromium depletion) and to creep by grain boundary pinning. The physical and mechanical properties of the alloy are representative of the AISI 300 family of austenitic steels. However, the room temperature yield stress and high temperature creep resistance are somewhat larger (compared with 316L) as a result of the presence of the titanium carbide precipitates, typically around 1 μm in dimension, that tend to nucleate on grain boundaries. The flat surfaces (i.e. the longitudinal-transverse, L-T, direction) from the original plate were left as-received (i.e. mill finish). The two plate ends (i.e. the short-transverse, S-T, direction) were coarse-cut using a bandsaw, while one of the plate edges (i.e. the longitudinal-short, L-S, direction) was ground parallel to the rolling direction to provide a nominally flat surface (Fig. 1).

The remaining plate edge was machined using a Hurco Hawk 30 milling machine, using a Sandvik Coromill general-purpose, solid